Flight Performance of the Hybrid Energy Storage System Payload Onboard the CSUNSat1 CubeSat

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Outline

- Overview of CSUNSat1 Project
- Flight launch from ISS
- Primary mission phase
  - Performance testing
- Extended mission phase
  - Life testing
  - Model development and flight validation
- Summary
- Acknowledgement

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CSUNSat1 Team

- JPL Energy Storage Team
  - Keith Chin
  - Marshall Smart
  - Erik Brandon
  - Joseph Stiles (intern)
- Gary Bolotin – System Engineer
- John Baker – Lunar Flashlight Mision Manager
- Prof. James Flynn – CSUNSat1 Lead)

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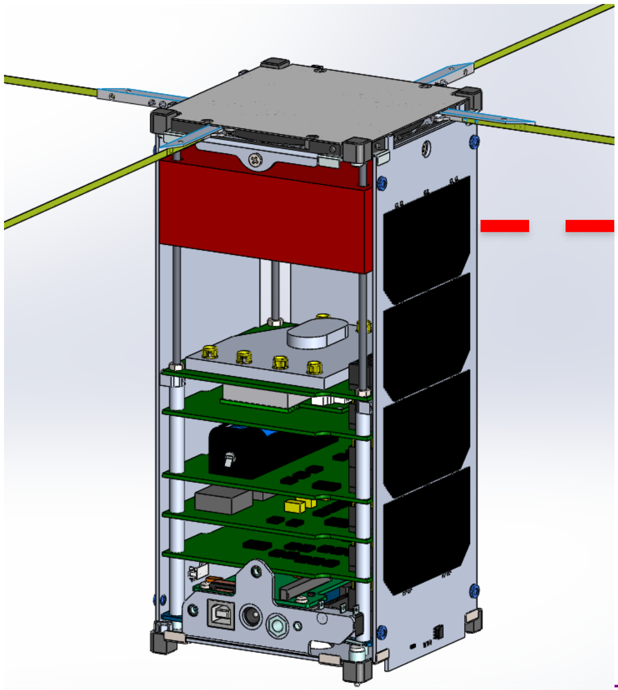
CSUN/JPL Collaboration Program

- **Funded by NASA's 2013 Small Spacecraft Technology Program (1 FTE/yr for 2 yrs)**
- Time frame: 11/1/2013 – 9/27/2015



JPL Energy Storage Payload

CSUNSat1: 2U CubeSat
- **Processor**
- **Communications**
- **Power System**

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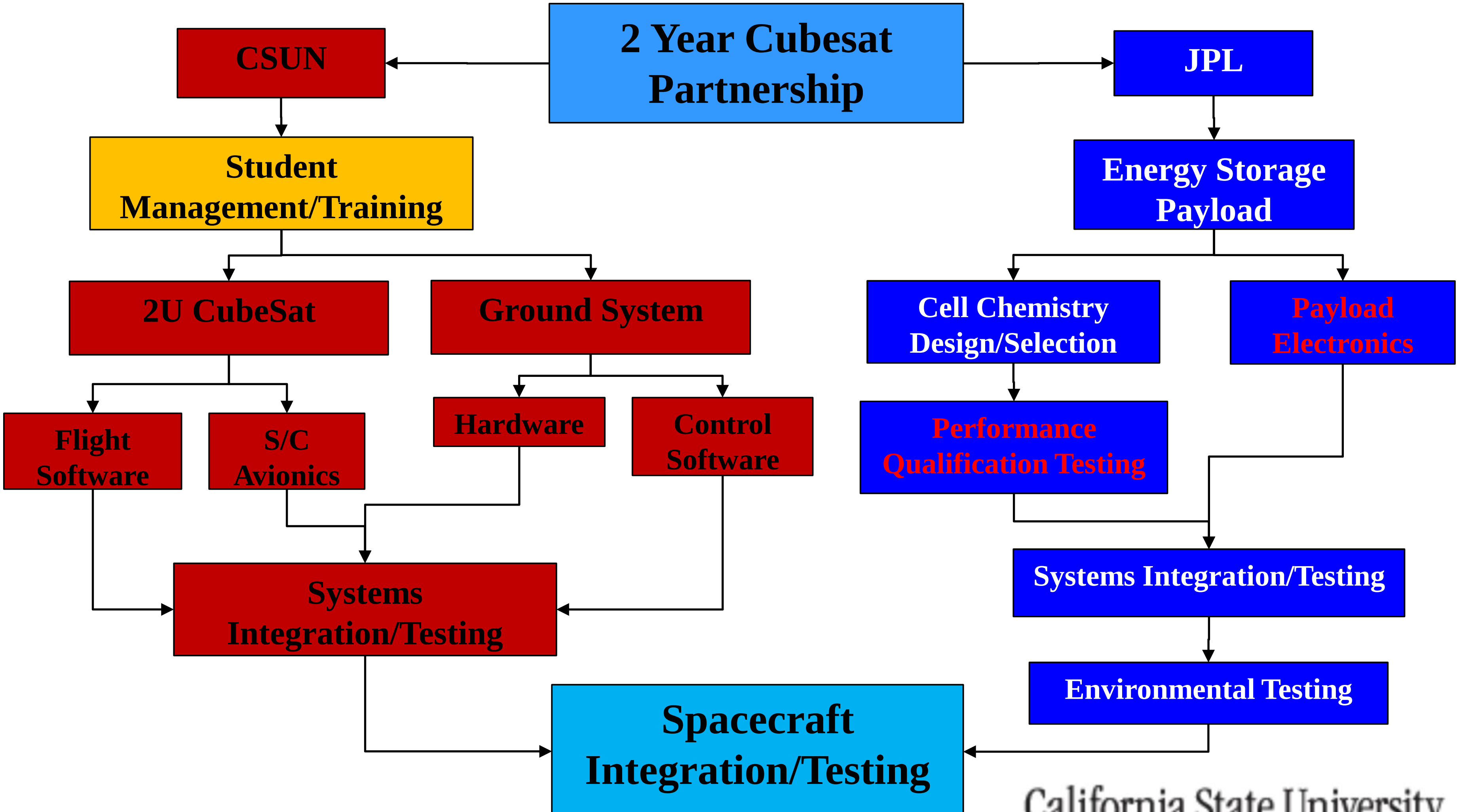
Program Activity Flowchart



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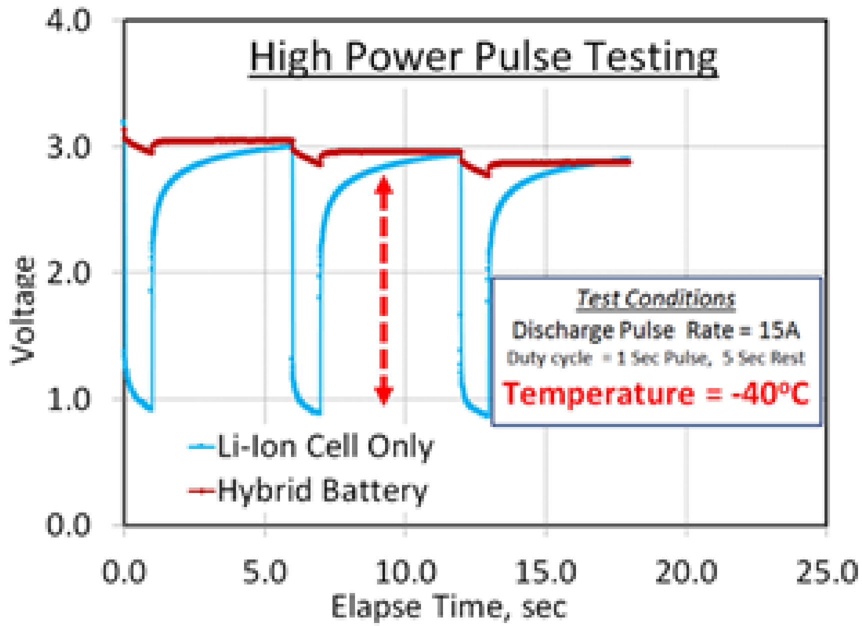
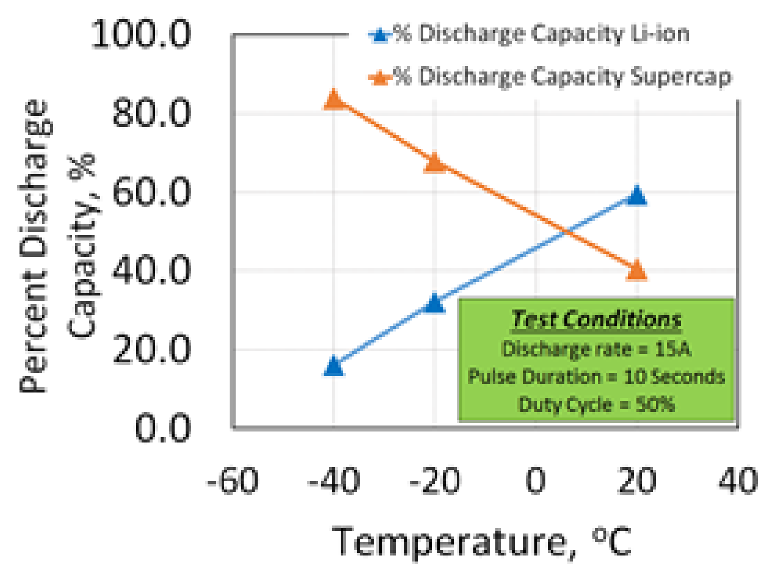
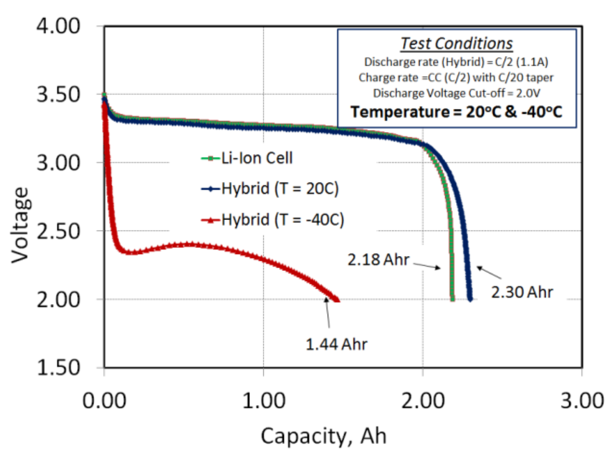
JPL Hybrid Performance Testing







- **Excellent capacity retention at -40°C.**
- **Enhanced usage life from load-sharing.**

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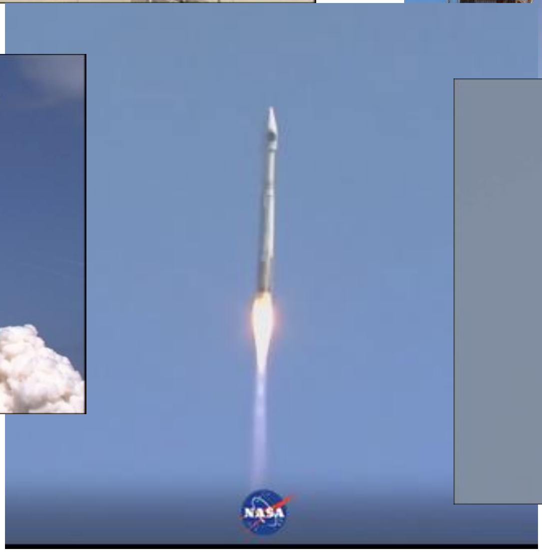
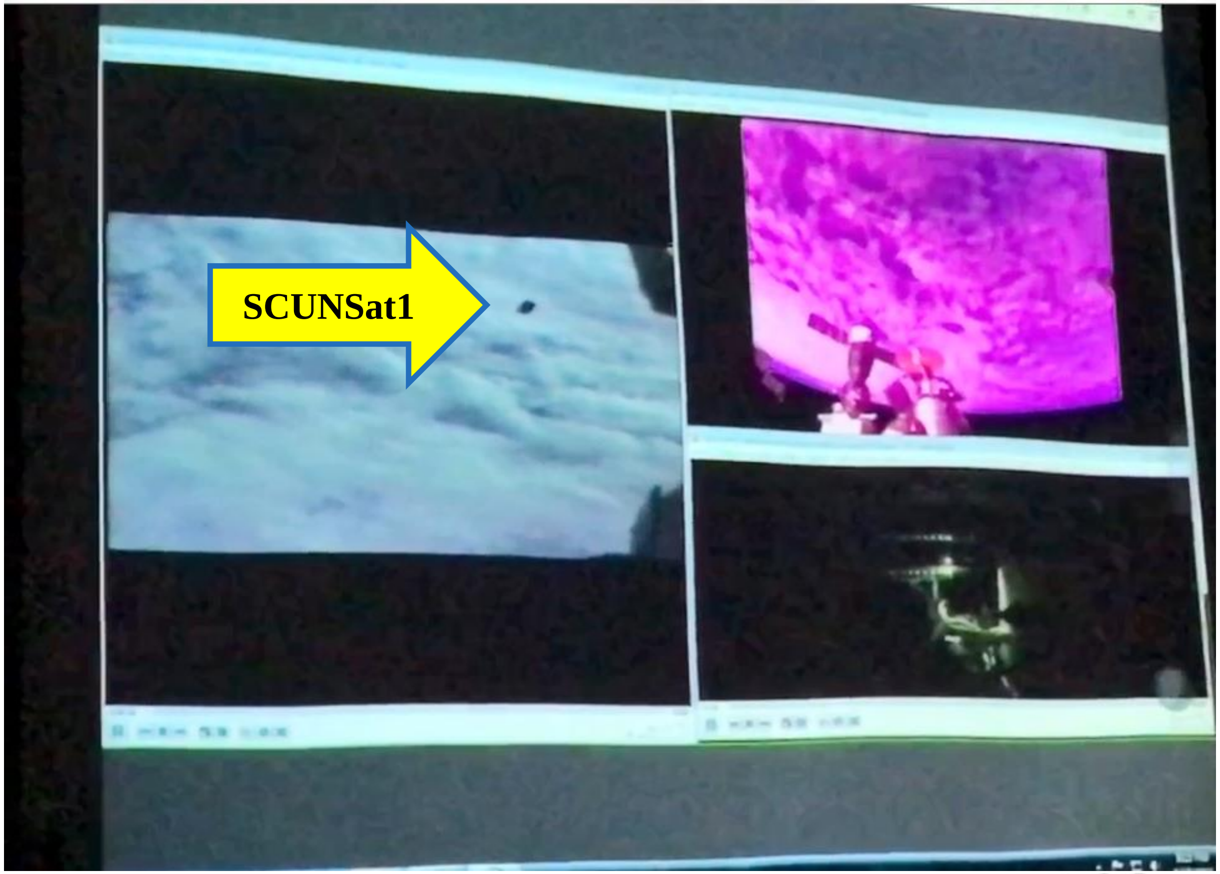
CSUNSat1 Launch from Cape on April 18th, 2017!!



CSUNSat1 Launch from ISS on May 17, 2017, 041500 GMT!!



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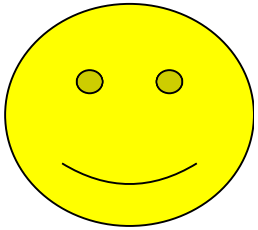
Primary Mission

- CSUNSat1flight system checkout
  - Payload battery functional test.
  - Charge/discharge in battery, supercapacitor, and hybrid mode.
- Payload thermodynamic performance characterization
  - High power (>5C-rate) tests @ nominal temperatures > 0^{o}C
  - High power (>5C-rate) tests @ low temperature < 0^{o}C.
- *Pass/fail Criteria:*
  - *Both battery and supercapacitor functional.*
  - *Hybrid system is functional.*
  - *Capacity loss on the battery is < 10%.*



100% success!

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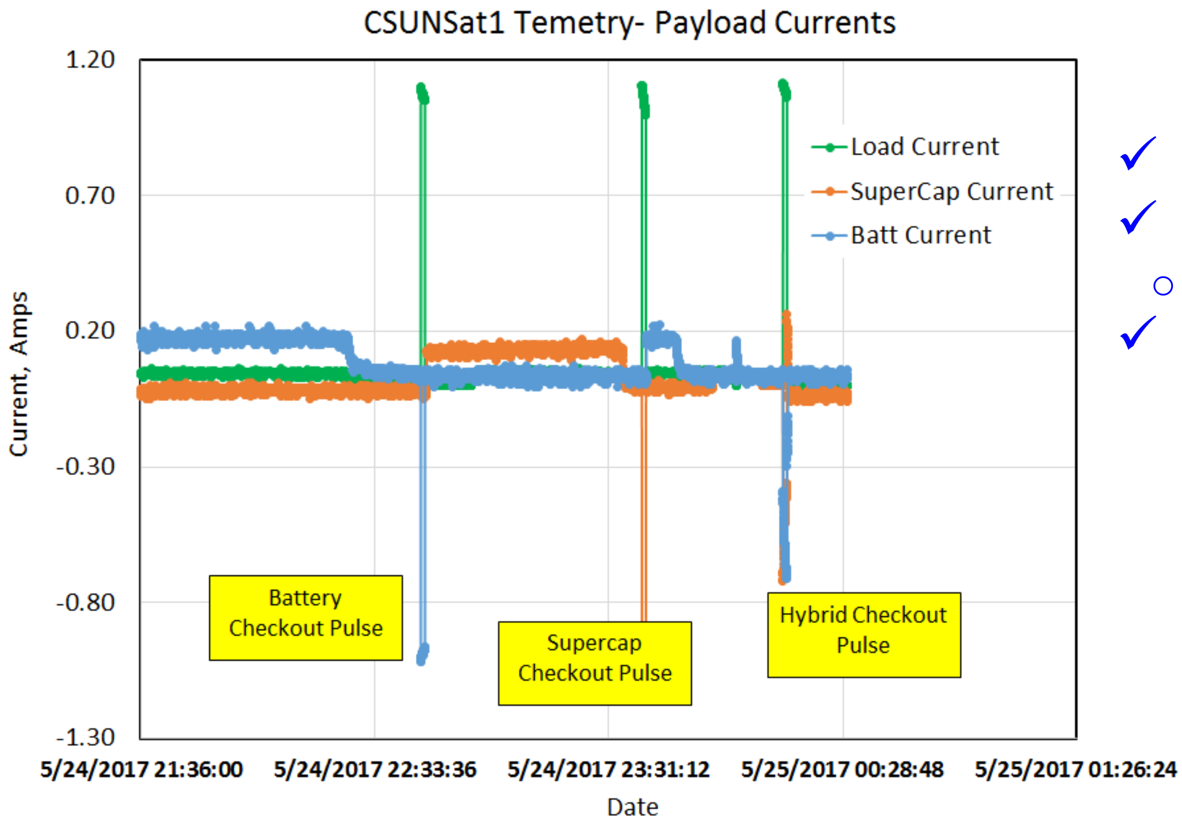
CSUNSat1 flight test data

Payload system checkout



- ✓ **CSUNSat1 all systems go!**
- ✓ **Battery is in good health**
  - ○ **Battery voltage > 3.0V (3.3 BOL)**
- ✓ **SuperCaps are in good health**
  - ○ **<u>Capacitances</u> (310F nominal)**

  SuperCap1 = 317.8 F

  SuperCap2 = 302.1 F

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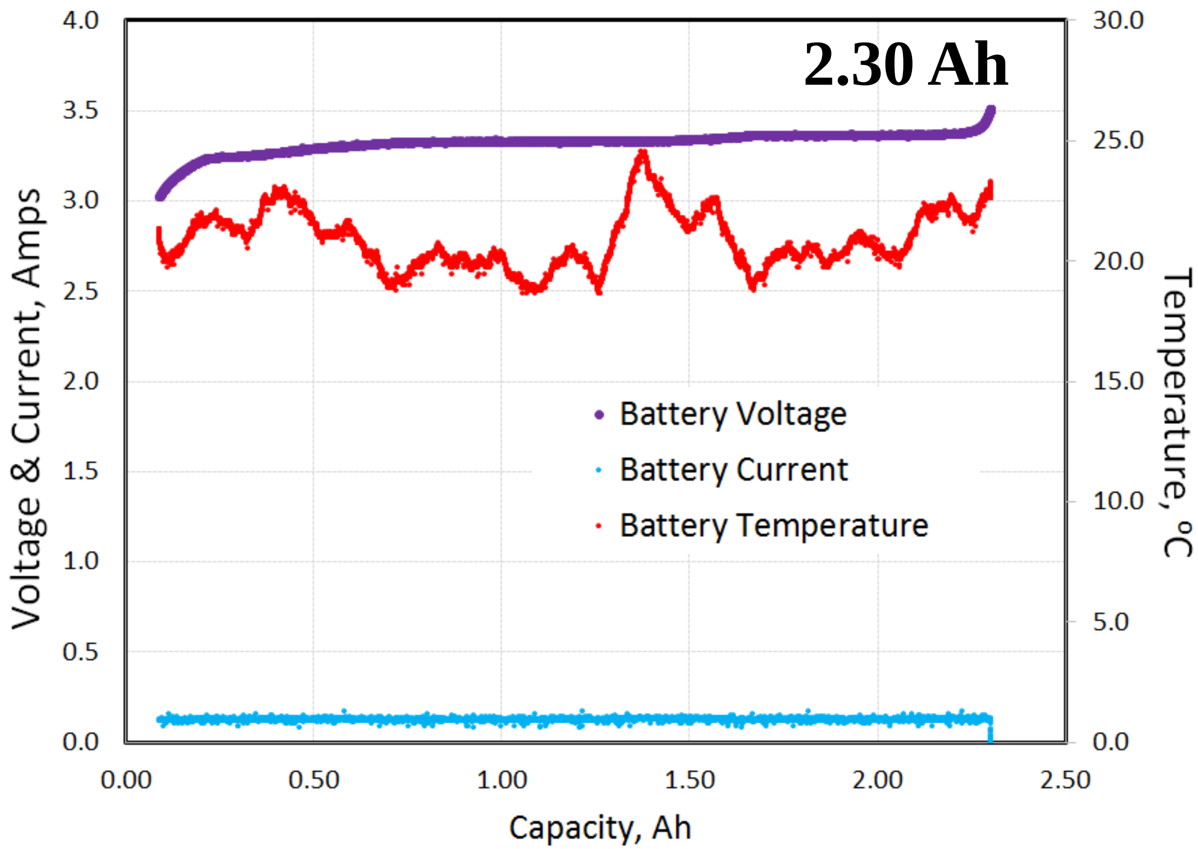
CSUNSat1 flight test data

Initial 24 hr charge cycle



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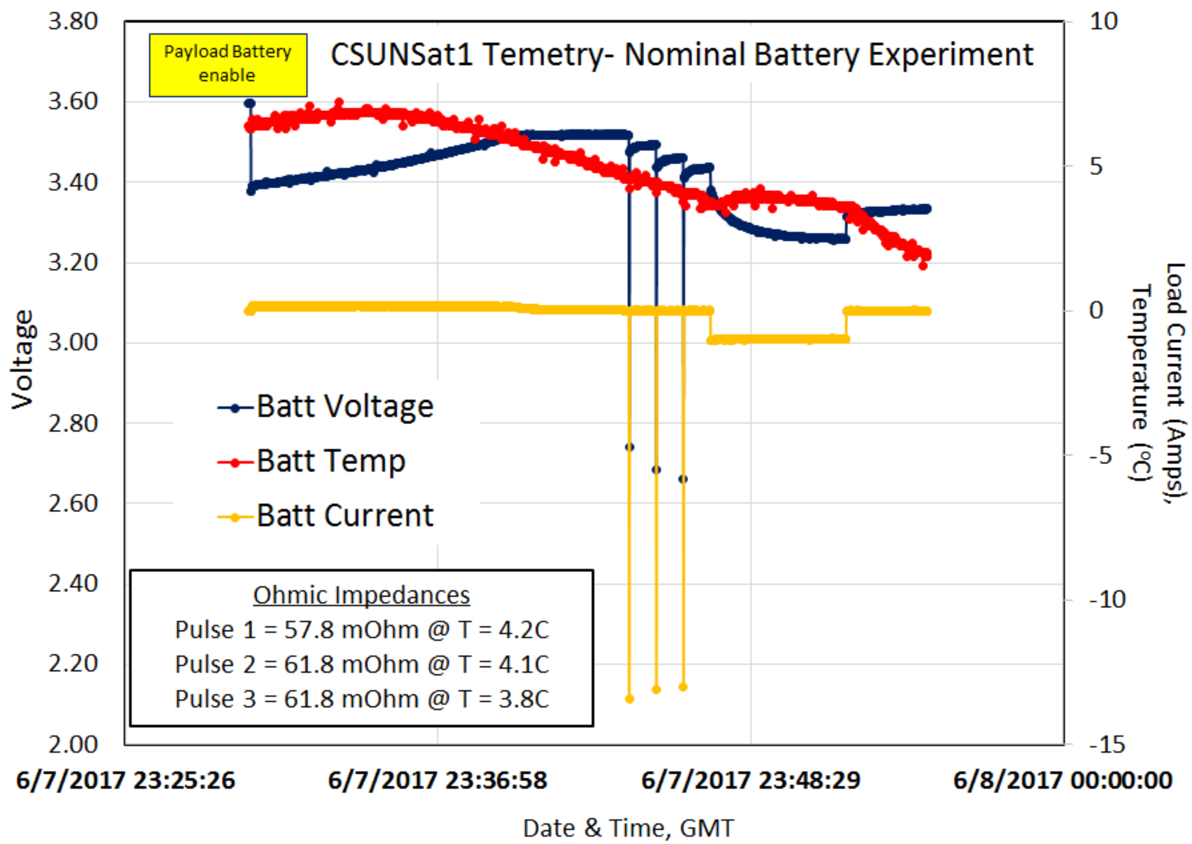
CSUNSat1 flight test data

Nominal temperatures



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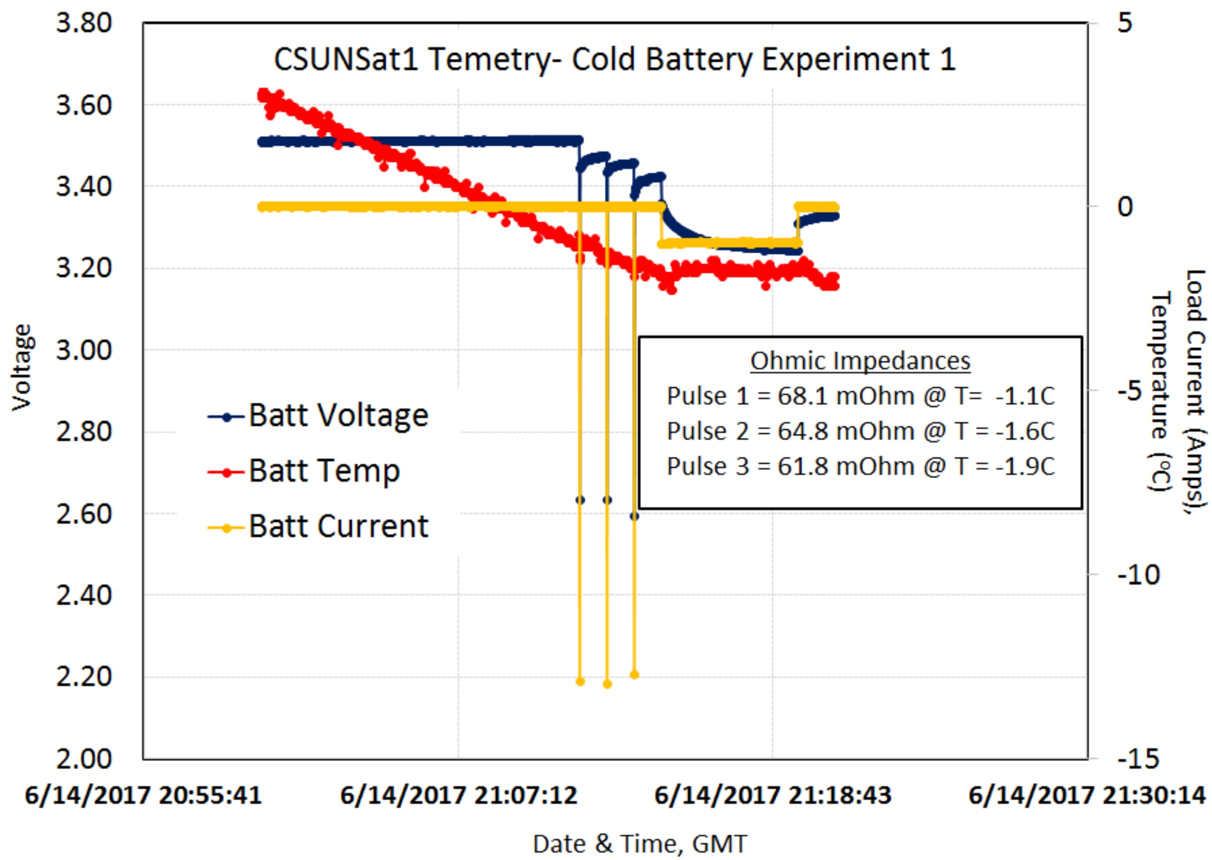
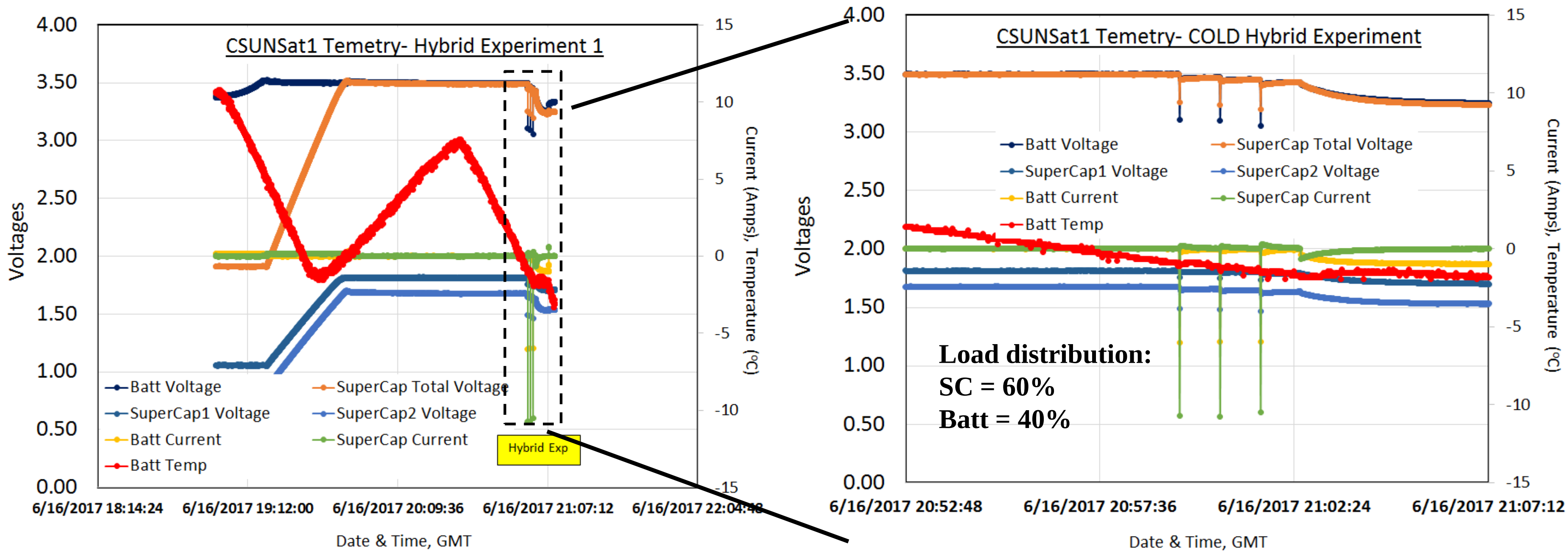
CSUNSat1 flight test data

Low temperatures



CSUNSat1 flight test data

Low temperatures



Pulse #	Batt Imp (mOhm)	SC Tot Imp (mOhm)	SC2 Imp (mOhm)	SC1 Imp (mOhm)	Temp (°C)
1	64.89	22.35	17.44	4.91	-1.10
2	62.83	21.19	16.07	5.12	-1.33
3	66.70	23.88	17.43	6.46	-1.57

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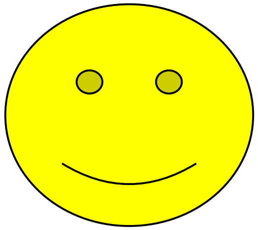
Extended Mission

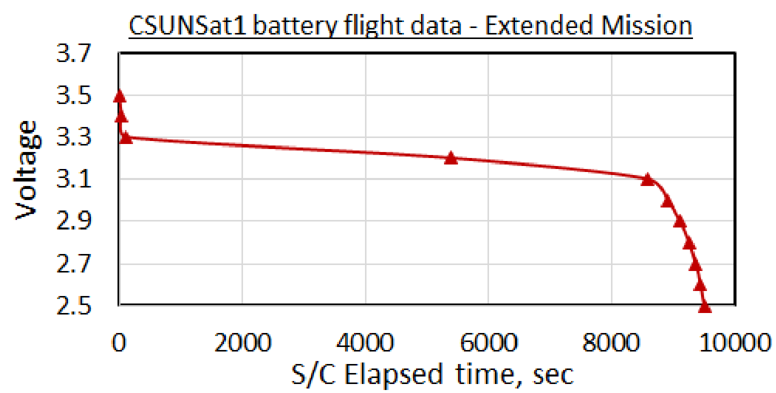
- Battery life characterization
- Battery performance model development
  - Model validation from CSUNSat1 flight data
- *Pass/fail Criteria:*
  - *Minimum of 10 full charge/discharge cycles.*
  - *Functional predictive model capabilities.*
  - *Model fidelity < 5% error.*



100% success!

CSUNSat1 Operational challenges

- Telemetry SD card failed during extended mission phase
- Thermal limitations of payload electronics board from dissipation due to prolonged high rate discharge.



Battery Model Basics

$$\boldsymbol{Capacity(t) = \int_{sim\_t_o}^{sim\_t_f} i * dt}$$

$$\boldsymbol{SOC = \frac{Capacity(t)}{100\%Cap(Temp, usage)}}$$

$$V(t) = V_o + \eta$$

Over-potential

$$\eta = Load \ * Impedance\boldsymbol{s}$$

$$\boldsymbol{Impedance} = f(Ohmic, ChargeTransfer, MassTransfer)$$

$$\boldsymbol{Parameterization} = Impedance(Temp, SOC, time)$$

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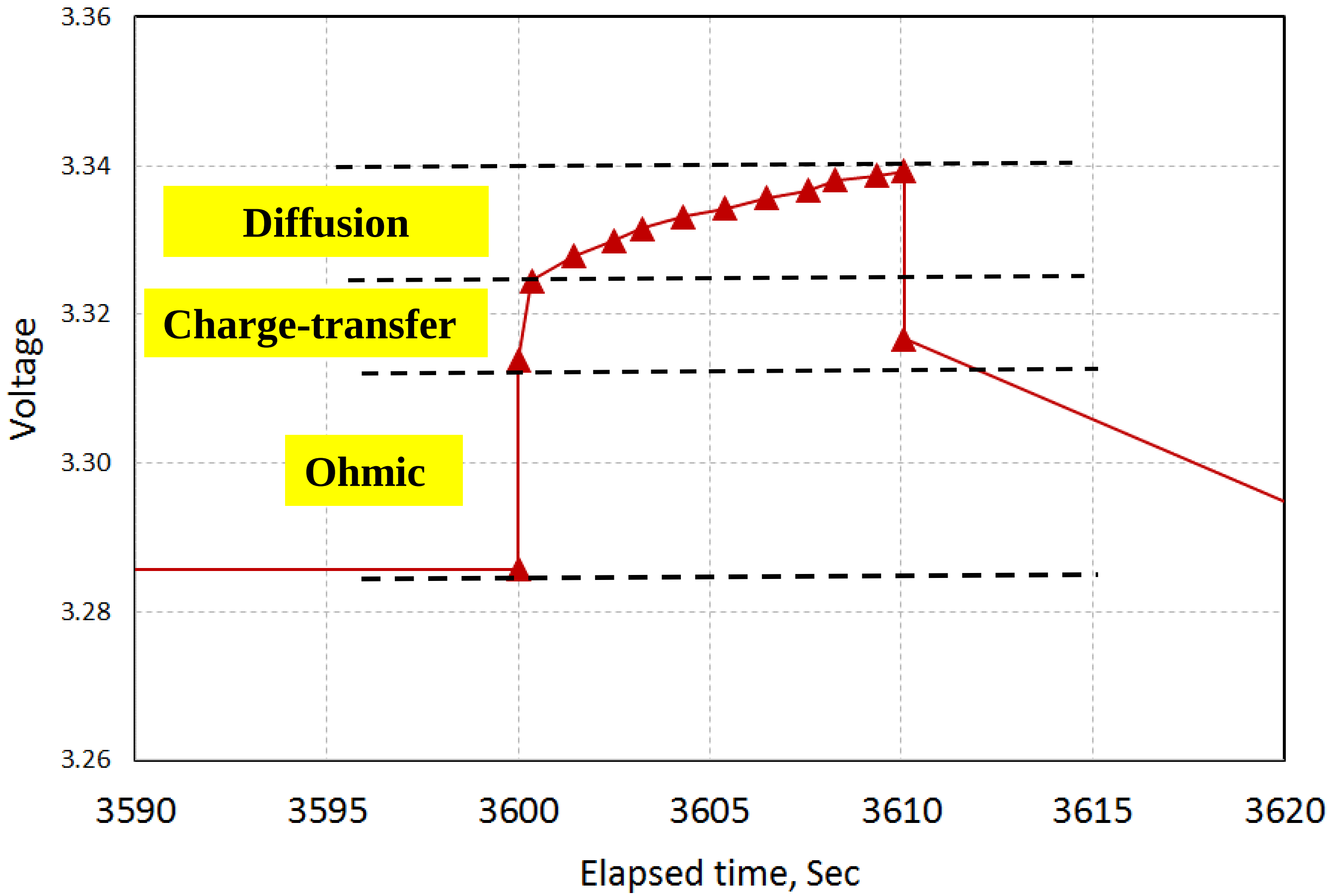
DC Impedance perspective



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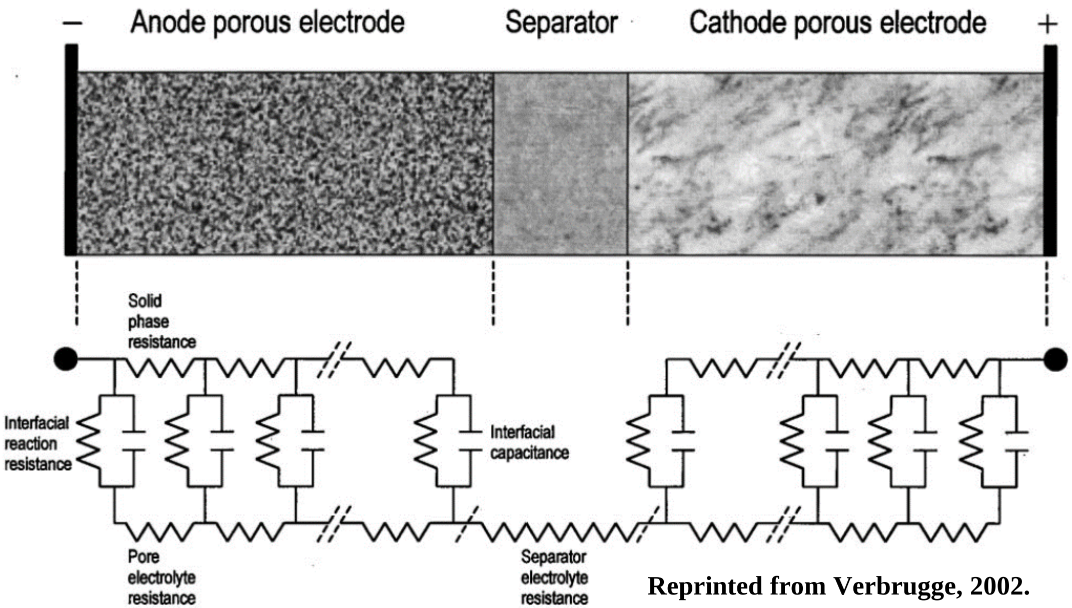
Battery physics from ac impedance



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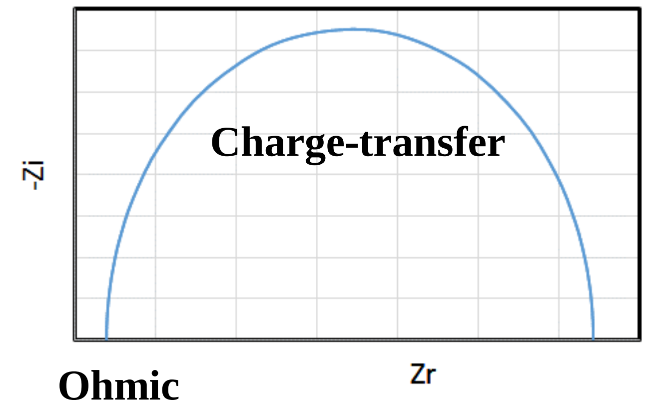

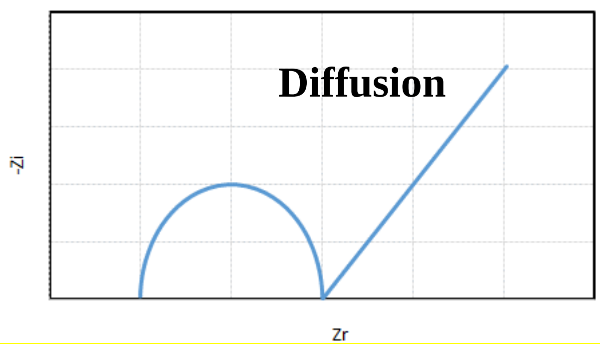

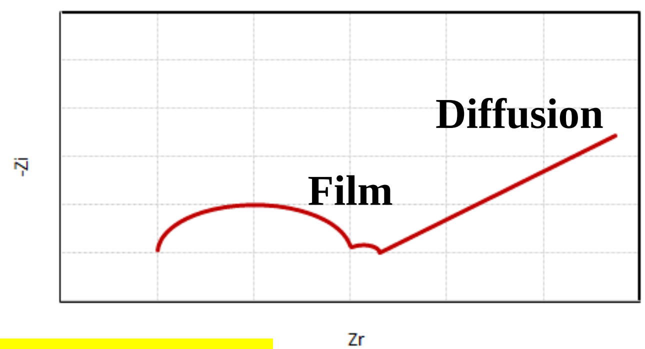

- **Basis for battery model: ohmic, charge-transfer, film, & mass-transfer impedances. It has physical basis, easily measurable, and representable mathematically for modeling purposes.**

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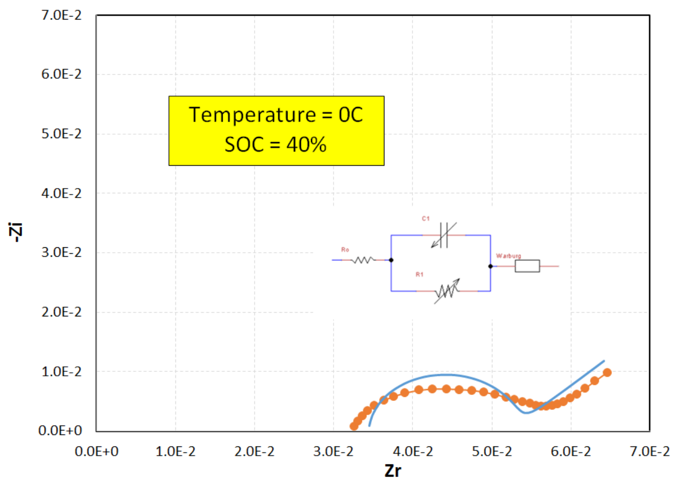
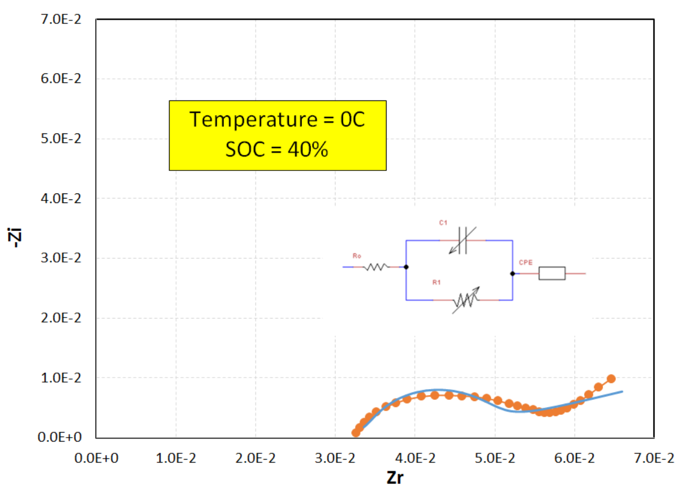
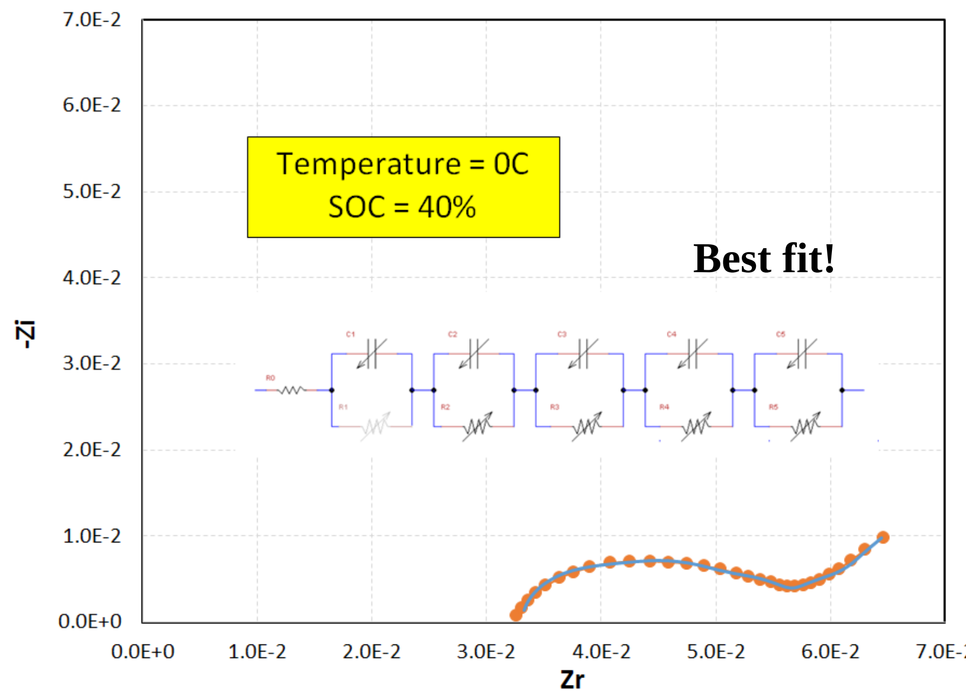
Circuit Modeling Fitting







- **Add RC-units provide substantially improved fit over Warburg & CPE.**

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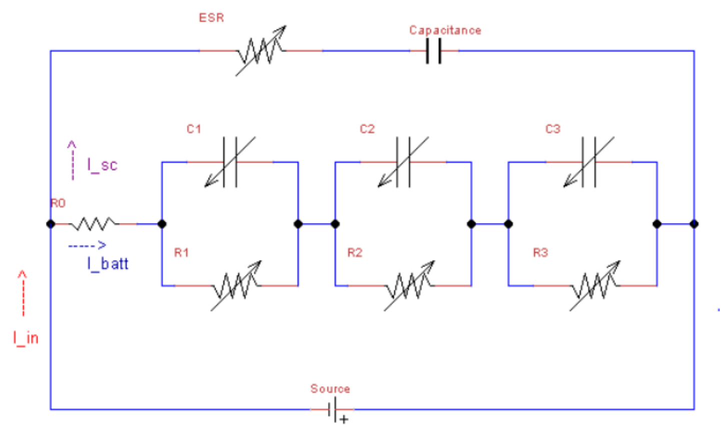
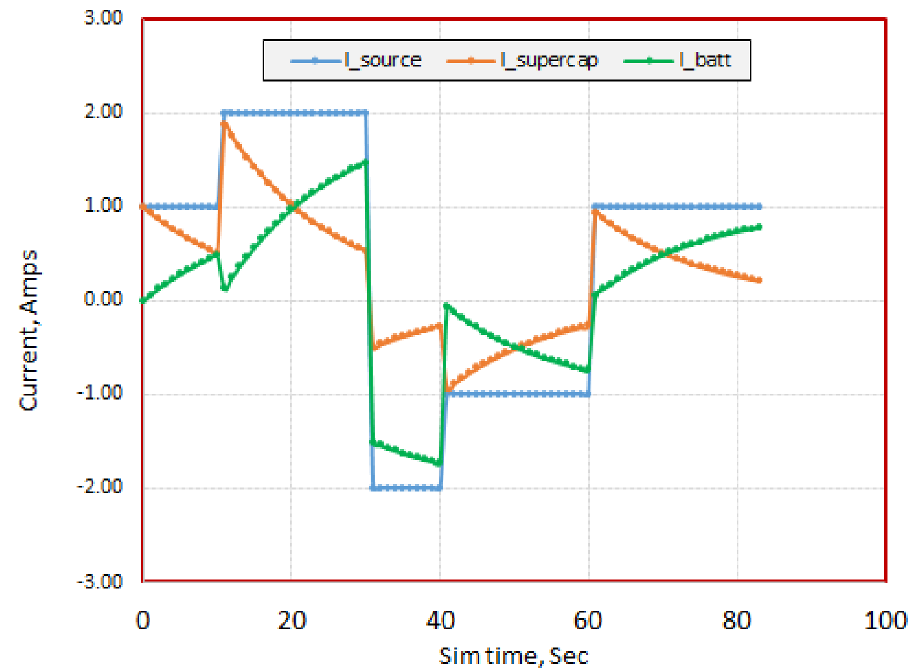
Hybrid Battery Model



Example of hybrid load distribution model:



Apply Kirchhoff's current and voltage laws:

$$I_{in} = I_{sc} + I_{batt}$$

$$\xi_{source} = I_o * R_{ESR} + \frac{q}{C_{supercap}}$$

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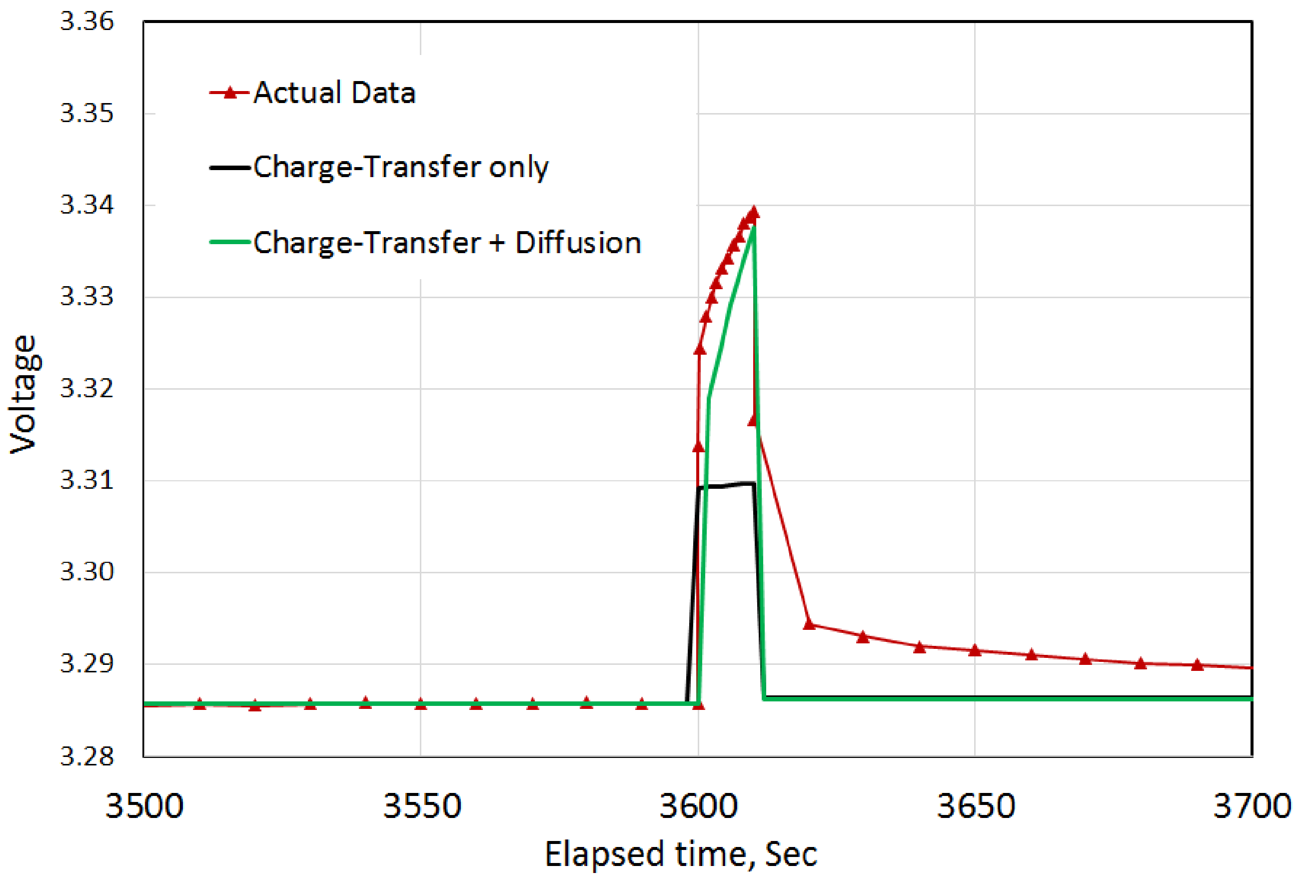
Voltage Model Validation:

Transients



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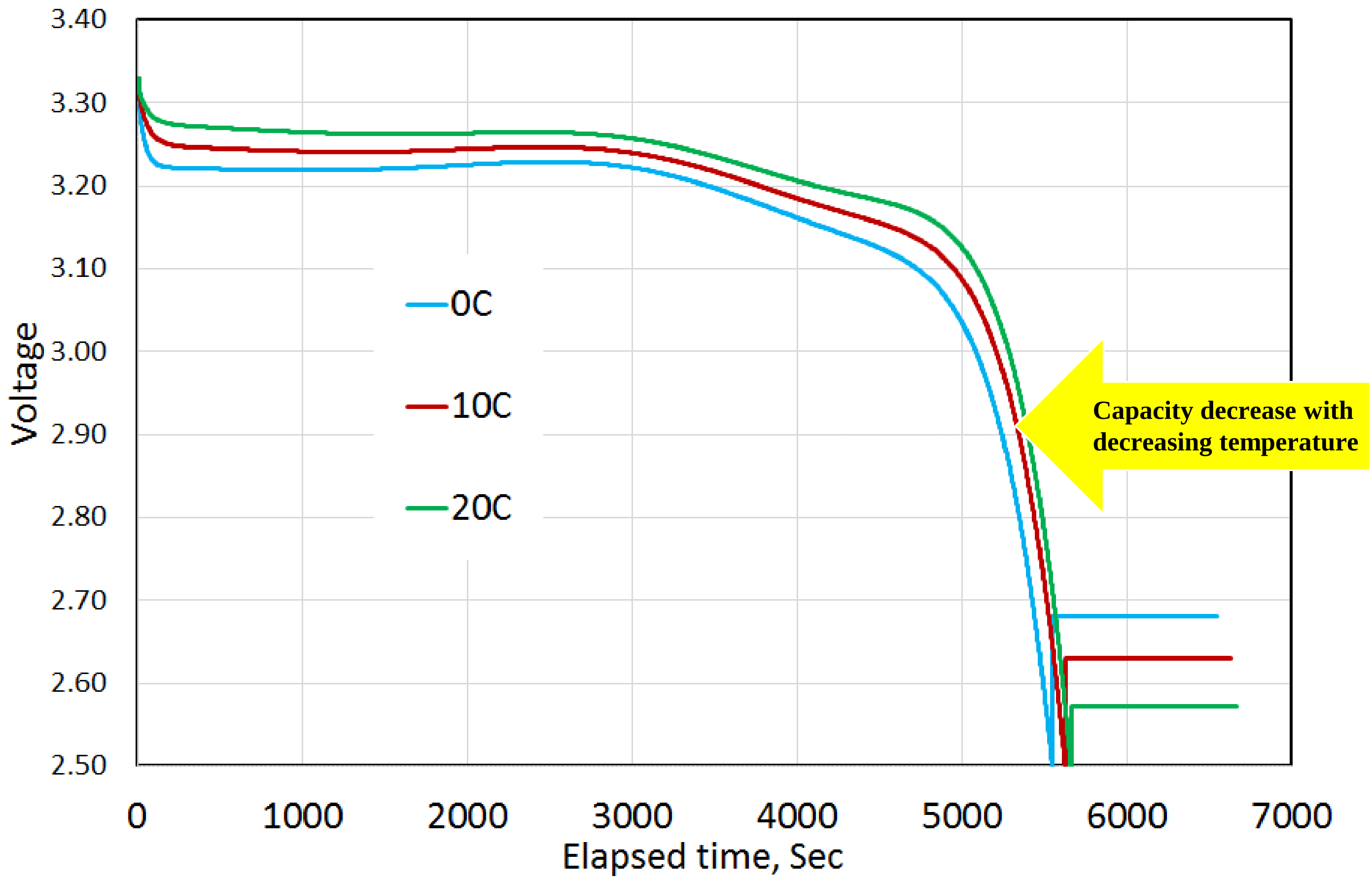
Voltage Model Validation:

Temperatures



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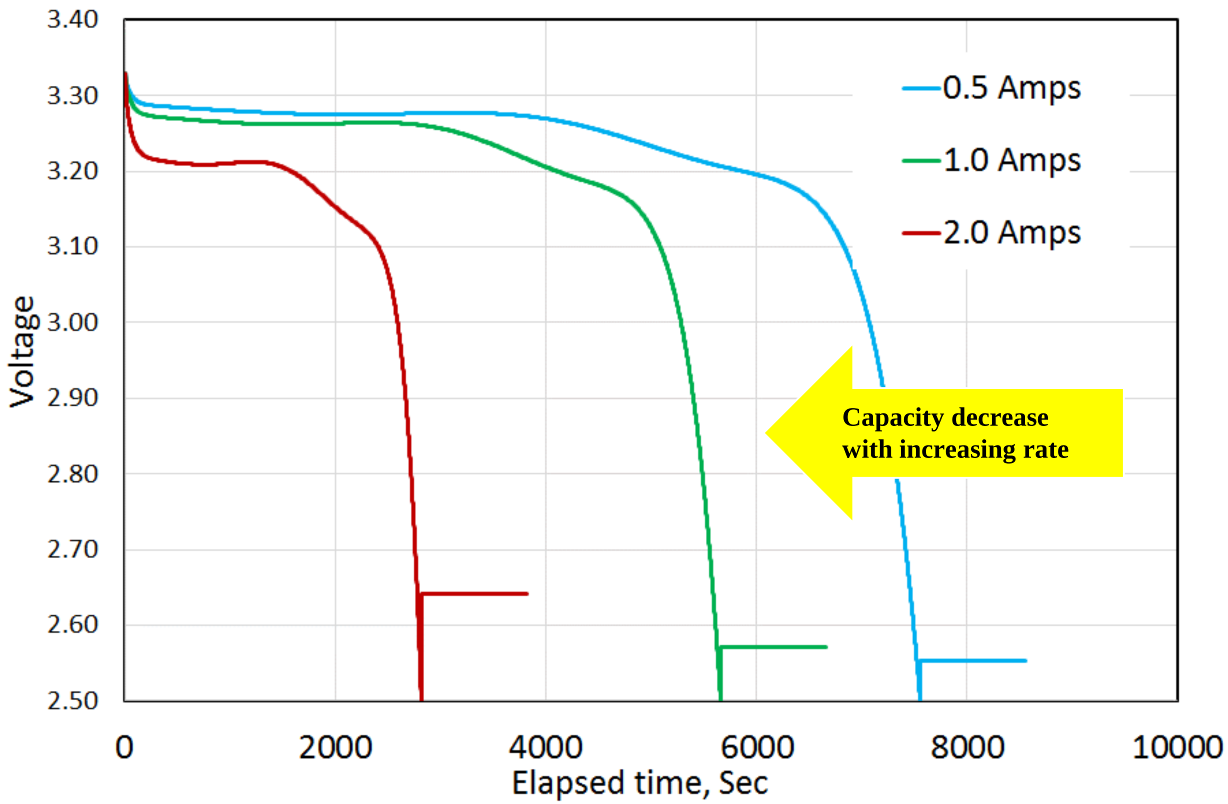
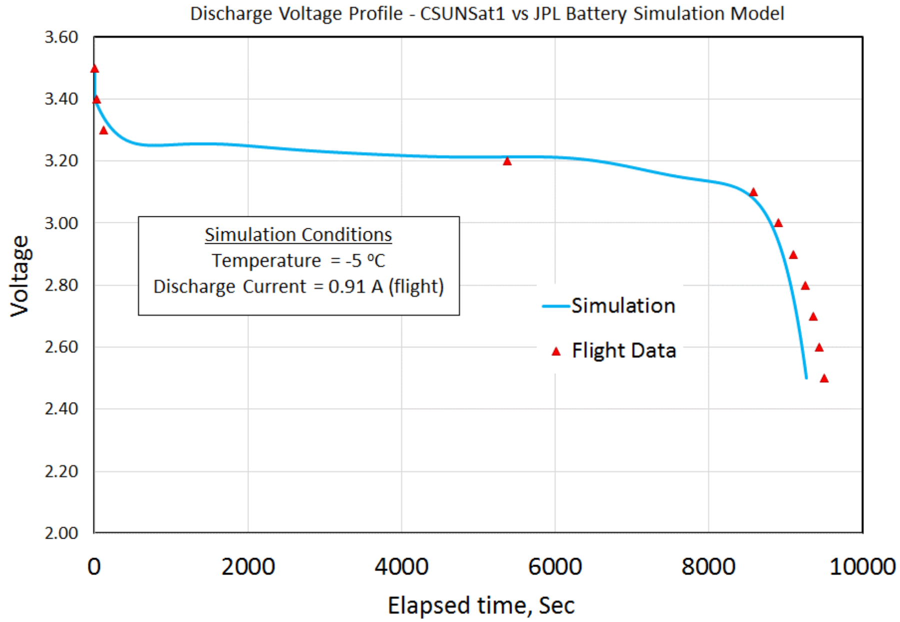
Voltage Model Validation:

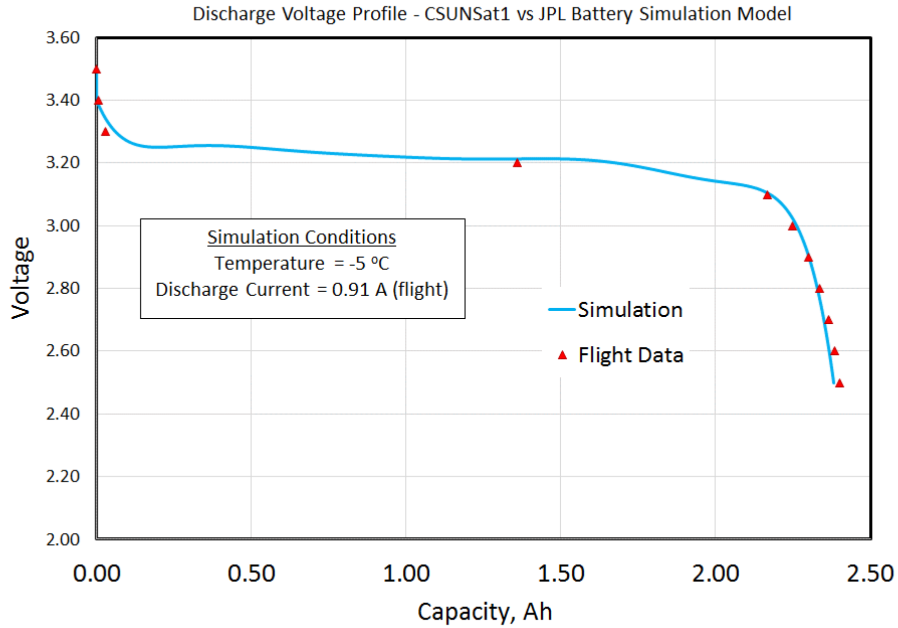
Current Rates



Flight Simulation Test Case:

CSUNSat1 payload telemetry





JPL simulated battery model successfully predicted CSUNSat1 hybrid battery performance on flight.

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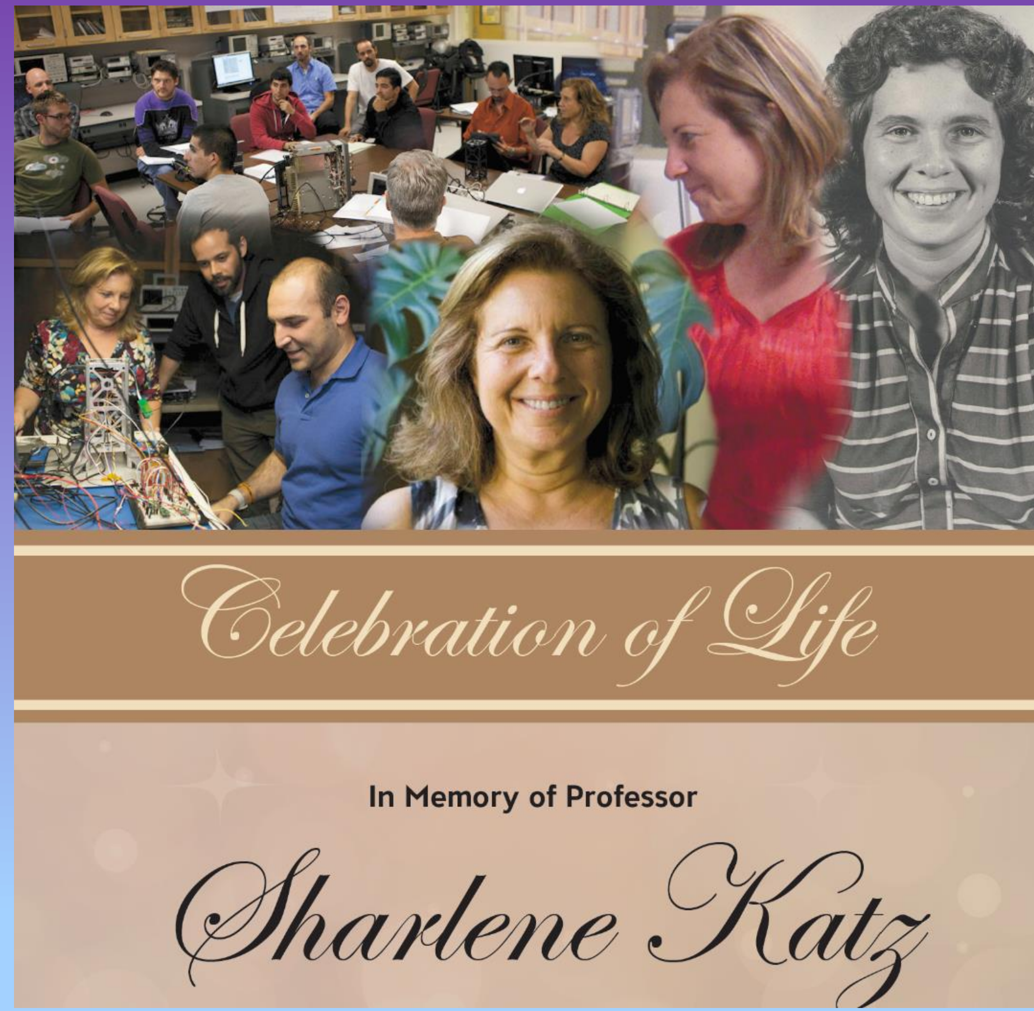
Summary

- CSUNSat1 project is **100% successful** in completing both primary and extended mission phases.
- CSUNSat1 operations provided flight heritage on an enhanced low-temperature high power capable hybrid energy storage system designed for deep space applications.
- CSUNSat1 cycle life flight telemetry provided validation of an impedance-based battery modeling technique for generic flight applications.
- Future work
  - ❖ Development of CSUNSat2 for science applications.

CSUNSat1 project is dedicated to the Life & Memory of <u>Dr. Sharlene Katz</u>, 1954 - 2017

-In honor of her excellence in engineering & education.



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